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The Energy Innovation Imperative

Addressing Oil Dependence, Climate Change, and Other 21st Century Energy Challenges

Society faces many energy challenges in this century, but "running out" of energy resources in a global or absolute sense is not one of them. The world may be running out of cheaply extractable and reliably deliverable conventional oil and natural gas, insofar as (a) these energy forms may continue (with some ups and downs) to get more costly and less reliable over time and (b) it is unclear for how much longer the rate at which they are extracted can be increased to meet rising global demand. But energy resources of other types are immensely larger and capable in principle of being expanded to multiples of today's use rates of oil and gas combined: there is 5 to 10 times as much coal as conventional oil and gas; there is 5 - 10 times as much oil shale and unconventional gas as coal; the energy potential of uranium and thorium resources is larger still; and harnessing even a small percentage of the solar energy flow reaching Earth's land surface could meet multiples of today's world energy demand.[1]

The energy issue is difficult not because of any impending exhaustion of global resources, then, but for more complicated reasons.

The first of these is the multiplicity and diversity of the economic, environmental, and security aims that energy strategy must serve, many of them in tension with each other (see box, following page). The desire to limit costs is often at odds with the aims of increasing reliability, reducing vulnerability, and improving environmental performance. The historically low costs of oil, natural gas, and many hydropower projects are not likely to be matched by the more abundant fossil, nuclear, and renewable alternatives. Expanding domestic oil production in order to limit imports eventually encounters not only rising marginal costs but

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Aims of a Successful Energy Strategy

Choices about how society obtains and uses energy are crucial determinants of economic well-being, environmental quality and sustainability, and national and international security. A successful energy strategy must attend to these connections by pursuing multiple aims. Among those widely considered important are:

Economic aims
- ensuring reliable supplies of fuel and electricity for basic needs and economic growth;
- limiting the costs of energy to firms and consumers;
- limiting balance-of-payments impacts and macroeconomic vulnerabilities from energy imports.

Environmental aims
- improving urban and regional air quality;
- limiting impacts of energy development on fragile ecosystems;
- avoiding nuclear-reactor accidents and waste-management mishaps;
- limiting energy-supply contributions to global climate change.

National and international security aims
- minimizing dangers of conflict over oil and gas resources;
- avoiding the spread of nuclear weapons from nuclear-energy technology;
- reducing the vulnerability of energy systems to terrorist attack;
- avoiding energy blunders that perpetuate or create deprivation (which is one of the most fundamental causes of conflict).

also rising opposition when the remaining domestic resources lie under fragile or particularly highly prized environments. Replacing conventional oil and gas with synthetic liquids and gases made from tar sands, oil shales, and coal will sharply increase the emissions of climate-altering carbon dioxide unless costly carbon capture and sequestration accompany these conversions. Rapid expansion of nuclear energy may risk outrunning the capabilities of national and international organizations to manage its risks. And so on.

The second reason the energy issue is so challenging is the fact that no known energy source is free of significant limitations, liabilities, or uncertainties in relation to one or more of the important aims. That is, there is no technological "silver bullet". Volumes have been written about the character of the major energy options and the difficulties and uncertainties that cloud their prospects. Here I will characterize the question marks more tersely:

Conventional Oil and Gas—Not enough resources? This is a matter not only of global availability, of course, but also of economically and politically challenging

geographic distribution.

Coal, Tar Sands, Oil Shale—Not enough atmosphere? This refers to the capacity of the atmosphere to absorb without intolerable consequences the emissions from mobilizing and burning these immense fossil-fuel resources, above all the carbon dioxide.

Biofuels—Not enough land? Growing biofuels must compete for land and water with production of food, fiber, and chemical feedstocks, as well as with the essential environmental service functions of lightly exploited and unexploited ecosystems.

Wind and Hydropower—Not enough acceptable sites? Wind and hydro are most economical in places where the respective resources are highly concentrated and near load centers; not only do costs tend to go up as increasing scale of use drives society to less attractive sites, but many of the best sites are prized for other purposes and may be placed off limits by politics.

Solar Photovoltaics—Not enough money? Despite decades of remarkable progress in cost reduction, solar photovoltaic arrays remain several times more expensive than fossil-fueled, nuclear, and wind electricity generation for grid-connected applications. How much cheaper photovoltaics can get—and how much costlier their competition might get—remain unclear.

Ocean Energy—Too costly and too disruptive? Harnessing tides by damming estuaries is both costly and highly disruptive environmentally. Turbines in tidal straits and devices for harnessing wave energy must be both inexpensive and robust in the hostile marine environment; the needed combination may be unattainable. Ocean thermal energy conversion must move immense quantities of sea water in order to extract a tiny fraction of its energy; whether the undersea equipment involved can be made both cheap enough and survivable enough is unclear, as are the ecological consequences of large-scale use.

Nuclear Fission—Too unforgiving? Nuclear fission is unforgiving of error in design and operation of reactors, reprocessing plants, fuel-fabrication facilities, and waste transport and disposal—and unforgiving of malice by those who would attack the facilities for economic and public-health impact or divert the technology and materials for making nuclear weapons. Whether improvements in technology and management can outpace the growth in the opportunities for error and malice as the nuclear enterprise grows is unclear. If nuclear energy were to undergo large expansion and *then* prove unacceptable to the public because of high incidence of accidents and/or terrorism in the expanded enterprise, the economic disruption from shutting it down would be large.

Nuclear Fusion—Too difficult? After more than 50 years of effort and the expenditure of perhaps 30 billion current U.S. dollars in fusion R&D worldwide, the best-performing devices aimed at harnessing for power production the process that powers the stars and hydrogen bombs still require more energy to run than they produce. The obstacles to ultimate success lie not only in the physics of confining fusion fuel at its ignition temperature of 100 million degrees C or more, but

also in the advances in materials science and systems engineering needed to build a reliable and affordable reactor around a fusion fire.

Hydrogen—Only an energy carrier, not a source. Chemically unbound hydrogen does not exist in significant quantities on Earth, and extracting it from the forms in which it is most abundantly found—water and hydrocarbons—costs more energy than chemical reactions of the resulting hydrogen can yield. If controlled fusion succeeds, the heavy hydrogen isotopes and perhaps even ordinary hydrogen would become *nuclear* fuels…but see above. Unless and until fusion succeeds, hydrogen will remain merely an energy carrier that, like electricity, may be prized for its convenience, versatility, and low environmental impact at the point of end use, but requires the use of a primary energy source for its production.

Improving Energy-End-Use Efficiency—Not enough education? Increasing the efficiency with which energy is converted into the goods and services that people want—comfort, mobility, illumination, refrigeration, the powering of industrial processes, and so on—is equivalent to an energy source, because kilowatt-hours or liters of fuel saved in one application can be used for another. Such end-use-efficiency improvements are (and are destined to remain for some time to come) the cheapest, cleanest, surest, most rapidly expandable energy option we have. The ultimate limits on this option are imposed by thermodynamics, but much more salient today are the limits imposed on the expandability of end-use-efficiency improvements by lack of knowledge by firms and consumers about the opportunities that exist and how to exploit them.

Beyond competing goals and the lack of a silver bullet, the third major reason the energy issue is so challenging is the large embodied capital investment and long turnover times of the world's energy-supply and end-use systems, which create large hurdles to transforming those systems as rapidly as the determinants of what is desirable and necessary are changing. The replacement cost of today's global energy-supply system—all of the power plants, transmission lines, drilling rigs, pipelines, refineries, coal mines, and so on—is in the range of $12 trillion, and this immense capital investment turns over with a characteristic time of 30-40 years, the average operating lifetime of the facilities involved. The stock of energy-using artifacts—buildings, appliances, cars and trucks, airplanes, industrial machinery—represents an even larger investment, with turnover times ranging from somewhat shorter (cars, appliances) than that of energy-supply facilities to considerably longer (buildings). Adding to the inertia created by these huge investments and long time scales is the entrenched economic and political power of the organizations—public as well as private—that achieved their powerful positions by creating and sustaining the historical and current patterns of energy supply and demand and are understandably interested in preserving that status quo.

The energy-system inertia that results from these circumstances, combined with the typical multi-decade time scale for research, development, and demonstration to bring a new energy option even to the threshold of competitiveness with the entrenched approaches, means that it is possible and even likely for prob-

lems with the status quo to materialize more rapidly than the energy system can adjust to address them. When this timing mismatch is compounded by additional time lags in developing a scientific consensus about the harmful phenomena (as in the case of understanding both the health and the climate impacts of the emissions from fossil-fuel burning), the chances of being "locked in" to energy-system characteristics that impose higher than expected costs and risks for decades only increases.

THE TWO MOST DIFFICULT CHALLENGES

Reflection on what makes energy challenges difficult in general and on the particular characteristics of the challenges faced by the United States and the world in the early 21st century has led most thoughtful observers to the conclusion that two of those challenges stand out above all others in their combination of difficulty and danger. These are:

- how to reduce the macroeconomic vulnerability arising from oil dependence overall, and the balance-of-payments and foreign policy liabilities associated with the part that is imported, despite huge and growing liquid-fuel demands from the transport sector; and
- how to provide the affordable energy needed to sustain prosperity where it now exists, and to create and sustain it where it now doesn't, without entraining intolerable disruption of global climate by the emissions from fossil-fuel use.

These challenges would be daunting even if only wealthy, industrialized countries had to face them. But the difficulties (and, in some respects, the dangers) are larger still for the less developed world. And the solutions require that everybody get them right, because both the oil market and the machinery of climate are global.

The Oil Problem

In 2005, the United States used 20.7 million barrels of petroleum products per day (Mb/d), equivalent in energy content to 19.1 Mb/d of crude petroleum. This oil accounted for 40% of U.S. primary energy supply and nearly all of the energy used by the transport sector of the economy. U.S. net imports of crude petroleum and petroleum products in 2005 were equivalent to 12.5 Mb/d of crude petroleum, meaning the United States was dependent on imports for 65.4% of its oil.[2] This was the largest percentage and the largest absolute oil-import dependence in U.S. history. OPEC provided 41% of those imports, the Persian Gulf 17%. The cost of U.S. oil imports in 2005 was $231 billion, accounting for 30% of the net U.S. trade deficit in that year.

The "reference projection" of the U.S. Energy Information Administration (EIA) for 2030 shows an increase of U.S. consumption to 25.3 Mb/d of crude-oil equivalent, with the transport sector the dominant driver of the growth (as in the past).[3] Import dependence, under the reference projection, reaches 68% by 2030. OPEC's share of those imports—and of world petroleum supply—is expected to

grow over this period, consistent with the distribution of the world's remaining ultimately recoverable resources of conventional oil.

World oil production in 2005 was equivalent to about 80 Mb/d of crude petroleum, accounting for 34% of global primary energy supply. Nearly 40% of the oil production came from OPEC, and 64% of it moved in world trade. The EIA's 2006 reference forecast for 2030 shows world production reaching nearly 120 Mb/d. China's oil imports are forecasted to increase from 3 Mb/d in 2004 to circa 12 Mb/d in 2030 (comparable to U.S. oil imports today), more than half of that coming from the Persian Gulf.

The economic dimension and the international-security dimension of these oil dependencies are complicated and interconnected. Firstly, a country's economic vulnerability to oil-price shocks is proportional to the country's total dependence on oil, not just on its import dependence. That is so because, in a world market, an economy pays any increase in the per-barrel price on every barrel used, not just on the barrels imported. (Import share does matter in terms of balance of payments, of course.)

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The link to conflict arises because the extent of a major country's economic vulnerability in relation to oil—say, that of the United States or China—affects the chances that it will resort to military action to try to prevent or terminate supply disruptions and the attendant price shocks. It also affects a country's freedom of action in how it pursues other aspects of its foreign-policy agenda (for example, in the case of the United States, the way in which it pursues its homeland-security/counter-terrorism agenda in its relations with oil-producing countries, some of which export terrorism as well as oil).

In principle, the dangers of supply disruptions and price shocks can be alleviated in a number of ways: increasing domestic production of conventional oil in one's own country; encouraging such increases in other countries in diverse geographic regions; encouraging increased production of unconventional oil resources (heavy oils, tar sands, oil shale) in one's own and other countries; increasing the production of liquid fuels from coal and from biomass; and reducing the liquid-fuel intensity of economic activity (energy in liquid fuels divided by GDP) by a combination of shifting to non-liquid fuels (solids, gases, electricity) in some applications and increasing the energy efficiency of the remaining liquid-fueled activities (above all cars, trucks, buses, and aircraft).

In practice, most of these approaches suffer from severe limitations. Even if the United States opens the Arctic National Wildlife Refuge to oil production, it is unlikely that U.S. domestic production of petroleum can be prevented from continuing to gradually decline over the next 25 years. Prospects in most other countries—outside the unstable regions that are more part of the problem than part of the solution—are not much better. Unconventional oil resources are considerably more energy-intensive to produce—and more polluting—than conventional oil. Making synthetic oil from coal is costly, water-intensive and, with current technology, polluting.

Shifting from oil to natural gas has already happened to a significant extent in the electricity-generating, residential-heating, and industrial sectors of the United States and a number of other countries, but one of the ongoing consequences of this is the emergence of a global natural-gas market in which, as with oil, an increasing fraction of the supply seems destined to come from politically unpredictable regions. Continuing a shift to natural gas, therefore, may only succeed in replicating the problems of excessive dependence and vulnerability from which the world is trying to escape in the case of oil.

Expanding the use of biofuels and accelerating improvements in oil end-use efficiency, particularly in the transport sector, are more promising, but they are not happening rapidly enough to reverse the worldwide trend of increased oil and oil-import dependence. The EIA reference projection for the United States—which takes into account current trends, current policies, and current and projected energy prices and energy-technology characteristics—shows the U.S. share of oil in primary energy use still at 40% in 2030 while the fraction of oil imported increases. The EIA's reference projection for the world as a whole has the share of primary energy provided by oil increasing over this period, and the fraction of world oil moved in world trade likewise increases in the reference case. Achieving a significant decline in the world's dependence on oil and oil imports in this period will require, evidently, far bigger increases in substitutes for oil and in oil-end-use efficiency than currently seem to be in store.

The Climate-Change Problem

Global climate change is increasingly recognized as both the most dangerous and the most intractable of all of energy's environmental impacts—indeed, the most dangerous and intractable of all of civilization's environmental impacts, period.

It is the *most dangerous* because climate is the "envelope" within which all other environmental conditions and processes operate. That envelope is not just a matter of global-average surface temperature (to which the misleadingly innocuous term "global warming" applies) but of averages and extremes of hot and cold, wet and dry, snowpack and snowmelt, wind and storm tracks, and ocean currents and upwellings; and not just the magnitude and geographic distribution of all of these, but also the timing. Distortions of this envelope of the magnitude that are underway and in prospect are likely to so badly disrupt the environmental conditions

and processes influenced by climate as to adversely affect every dimension of human well-being that is tied to the environment, including:

- the productivity of farms, forests, and fisheries;
- the geography of disease;
- the prevalence of oppressive heat and humidity;
- the damages to be expected from storms, floods, and wildfires;
- the property losses to be expected from sea-level rise;
- the expenditures that must be made on engineered environments (e.g., dams, dikes, air-conditioned spaces); and
- the distribution and abundance of valued species as well as pests.

Global climate change is the *most intractable* of environmental problems because the dominant driver of the disruption—emission of carbon dioxide (CO_2) from fossil-fuel combustion—is a deeply embedded consequence of the way in which civilization is today acquiring 80 percent of its energy.[4] Carbon dioxide is not a trace contaminant but a major combustion product, generated in immense quantities (about 27 billion metric tons of CO_2 from fossil-fuel burning worldwide in 2004). The global energy-supply system, as already noted, turns over only slowly, and the fossil-fuel-burning components around which 80% of it is based include some of the longest-lived components of all: coal-burning power plants can run for 60 years or more. This would be less problematic if the existing fossil-fuel burning technologies could be easily and inexpensively retrofitted to capture the CO_2 rather than releasing it to the atmosphere; but it appears that they cannot be. Capturing CO_2 and sequestering it away from the atmosphere is not easy; it is not cheap; and it appears to be much more difficult and costly in retrofit than for new technologies designed and located from scratch to have this ability.

While important aspects of the process of human-induced changes in global climate remain to be fully elucidated scientifically, including especially the exact timing and geographic distribution in which future impacts will unfold, there is no longer room for serious doubt about the basic characteristics of what is happening:

We know—from thermometer records in the atmosphere and the oceans, and from ice cores, bore holes, tree rings, corals, pollens, sediments, and more—that Earth's climate is now changing at a pace far outside the range of expected natural variation, and in the opposite direction from what the known, natural, cyclic influences on climate would otherwise be causing at this time.[5]

We should be cooling, but we are warming up: by ~0.8°C in global average surface temperature in the last 150 years, more over the continents, several times that over the continents at high latitudes. On a worldwide average, the 12 warmest years of the last 150 have all occurred since 1990, 20 of the 21 warmest since 1980. The last 50 years appear to have been the warmest half century in 6000 years.

As expected in a warming world, moreover, observations over recent decades also show that glaciers are retreating, sea ice is shrinking, Greenland and Antarctic ice is melting, permafrost is thawing, heat waves and wildfires are multiplying, and

storm and flood damages are soaring.[6]

A major part of the cause is clearly the well documented, human-caused buildup of heat-trapping gases ("greenhouse gases" or GHG) in the atmosphere, most importantly CO_2 from fossil-fuel combustion and deforestation but also methane, nitrous oxide, halocarbons, and tropospheric ozone. A buildup in the atmospheric concentration of heat-absorbing black soot has also been important, although the warming effects of the GHG and the soot have been partly cancelled by the cooling effect of a build-up of light-reflecting particles, likewise caused by human activities.

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Causality is established by the match between the magnitudes and the geographic and temporal patterns of the observed changes in atmospheric and oceanic temperatures with what theory and models say *should* result from the known buildup of atmospheric GHG concentrations that human activities have caused, after the effects of observed changes in anthropogenic and volcanic particulate matter and best estimates of changes in solar output are taken into account.

To be credible, the handful of "skeptics" about human causation of current global climate change would need *both* to explain what alternative mechanism could account for the pattern of changes that is being observed *and* to explain how it could be that the known human-caused buildup in GHG is *not* having the effects predicted for it by the sum of current climate-science knowledge (since, by assumption, something else is having these effects). No skeptic has met either test.

As for the future of human-caused changes in global climate, mid-range scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) and others project continuing increases of 0.2-0.4°C per decade in global-average surface temperature over the course of the 21st century, hence a 2-4°C increase between 2000 and 2100.[7] Mid-continent warming is expected to be 2 to 3 times greater, and high-latitude warming over the continents larger still. The Earth is then likely to be warmer than at any previous time in the tenure of Homo sapiens on the planet. In this scenario, the carbon dioxide concentration in 2100 will be

around 700 parts per million by volume (ppmv), compared to the pre-industrial level of about 280 ppmv; and CO_2 will be accounting for about 60% of the total warming influences from human changes to the atmosphere (the other main ones being increases in the concentrations of methane, nitrous oxide, halocarbons, tropospheric ozone, and black soot), compared to 45% in 2000. The increase in sea level by 2100, assigned a mid-range estimate of about half a meter by the IPCC in 2001, now seems capable of reaching several times that (although the matter remains highly uncertain).[8]

Faced with continuing climatic change of this magnitude on a "business as usual" trajectory, society has three options:

Human caused climate change is already occurring. Adaptation efforts are already taking place and must be expanded. But adaptation becomes costlier and less effective as the magnitude of climate change grows.

The first is *mitigation*, which means measures to reduce the pace and the magnitude of changes in global climate being caused by human activities. Examples of mitigation include reducing emissions of CO_2, other greenhouse gases, and black soot; enhancing "sinks" for greenhouse gases; and "geo-engineering" to counteract the warming effects of increases in greenhouse gases and soot that occur.

The second option is *adaptation*, which means measures to reduce the adverse impacts on human well-being resulting from the changes in climate that occur. Examples of adaptation include changing agricultural practices, strengthening defenses against climate-related disease, and building dams and dikes to control flooding and sea-level rise.

The third option is *suffering* the adverse impacts that are not avoided by either mitigation or adaptation.

Clearly, mitigation and adaptation are both essential. Human-caused climate change is already occurring. Adaptation efforts are already taking place and must be expanded. But adaptation becomes costlier and less effective as the magnitude of climate change grows. The greater the amount of mitigation that can be achieved at affordable cost, the more manageable will be the burdens placed on adaptation and the smaller will be the suffering that neither mitigation nor adaptation succeeds in avoiding.

The question of how much mitigation would be prudent is a crucial one for energy strategy, given the central role of fossil-fuel derived CO_2 in the climate problem. (Fossil-fuel burning added about 7.3 billion tonnes of C in carbon dioxide to the atmosphere in 2004; net deforestation probably contributed 1.5 to 2.5 billion tonnes, and cement manufacture about 0.2 billion tonnes.) Relevant here

is the goal embodied in the UN Framework Convention on Climate Change of 1992 (which was ratified by the United States and some 180 other countries). It calls for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". There was no formal consensus in 1992 as to what constitutes "dangerous anthropogenic interference", however, or on what level of greenhouse-gas concentrations would produce it. And there is still no formal consensus on these points.

It is becoming clear, nonetheless, that the *current* level of anthropogenic interference is dangerous. With the increase in global-average surface temperature above the pre-industrial level amounting only to about 0.8°C, the world is already experiencing rising incidence of floods, droughts, heat waves, wildfires, coral bleaching, summer melting of sea ice and permafrost, shrinkage of the mountain glaciers that stabilize the flows of many of the world's great rivers, drying out of rainforests, and category 4 and 5 cyclones, among other impacts. Owing to the thermal inertia of the oceans and the associated time lag in the climate system's coming to equilibrium with greenhouse-gas induced changes in the Earth's radiation balance, moreover, the global-average surface temperature would increase another 0.6°C even if the atmospheric concentrations of CO_2 and the other anthropogenic greenhouse gases were stabilized at today's values. Such instant stabilization cannot be achieved. Even if the growth of emissions could be halted immediately, the stabilized *emissions* would produce continuing growth in atmospheric *concentrations* because of the long residence time of greenhouse gases in the atmosphere (of the order of a century for CO_2).

Models of the global carbon cycle allow specifying the families of emissions trajectories over time that would lead to stabilization of the atmospheric CO_2 concentration at any given level above today's. (There is more than one trajectory for any given stabilization level, since the key characteristic is the cumulative emissions over century-scale periods; an emissions trajectory that stays on the "business as usual" path for some decades and then departs from it very sharply can have the same cumulative emissions as a trajectory that departs from "business as usual" sooner but more gradually.) Trajectories that change smoothly and relatively gradually, and that avoid concentrating too much of the burden of reductions on either the short term or the long term, are likely to be preferable from the standpoint of minimizing costs and societal disruption.

Emissions curves of this type that correspond to stabilizing atmospheric CO_2 at twice its preindustrial level—that is, at about 550 ppmv—start to deflect significantly from the "business as usual" trajectory around 2020, peak at emissions of circa 11 billion tonnes of C per year around 2040, decline to about 7 billion tonnes of C per year by 2100, and continue a gradual decline to about 3 billion tonnes of C per year in 2200. Under a mid-range estimate of the sensitivity of global-average surface temperature to CO_2 concentration, such a trajectory would produce an equilibrium increase of 3°C above the pre-industrial value if the other human and nonhuman warming and cooling influences on climate over this period cancelled

each other out (as happened approximately between 1750—the nominal pre-industrial benchmark—and 2000, and as could happen out to 2100 if reductions in non-CO_2 greenhouse gases are matched by reductions in the emissions of light-reflecting atmospheric particles and the pollutant gases that lead to formation of such particles).

Until a few years ago many analysts and groups were suggesting that stabilization of atmospheric concentrations at a level corresponding to a 3°C increase was in fact a suitable target—something of a compromise between the highest level at which climate-change impacts might be manageable (taking into account the potential for adaptation) and the lowest level that might be achievable (taking into account the known mitigation options and their estimated costs). The last few years of accumulating evidence about impacts already being encountered at only 0.8° C above the pre-industrial average temperature, however, have led many analysts to argue for a more ambitious target, with some (including the European Union) settling on 2°C. To have a good chance of holding the average warming to 2°C, the sum of the human influences would need to be held to the equivalent of CO_2's stabilizing at about 450 ppmv (compared to the 2005 value of 380 ppmv).[9]

An emissions curve corresponding to stabilizing atmospheric CO_2 at 450 ppmv should depart from "business as usual" much sooner than the curve for 550 ppmv—by about 2012. It should peak no higher than about 9 billion tonnes of C per year, around 2020, and should be down to about 3.5 billion tonnes per year by 2100 and 2.5 billion tonnes per year by 2200. (Of course, if the non-CO_2 influences on climate add up to a net warming over this period, the CO_2 emission curves would need to be even lower than described here in order for the overall effect to be equivalent to 550 or 450 ppmv of CO_2, respectively.) Mid-range "business as usual" (BAU) scenarios, by contrast, entail emissions around 20 billion tonnes of C per year in 2100.

The difference between the BAU path and the stabilization trajectories just described is immense. Cumulative emissions of C over the 21st century under a mid-range BAU path would be in the range of 1400 billion tonnes; for the indicated stabilization trajectories, cumulative emissions would be in the range of 500-800 billion tonnes of C (less if the non-CO_2 influences add up to a net warming). The difference of 600-900 billion tonnes measures the size of the mitigation challenge to which the world must rise to have a reasonable chance of averting climate-change disaster.

The types of approach available for this mitigation have already been mentioned. In brief, one can (i) reduce the offending emissions, (ii) increase the rate of removal of the offending substances from the atmosphere, or (iii) try to change other climate-relevant characteristics of the environment to offset the warming influences of those substances. Taking these in reverse order…

The third approach is worthy of further study, but the "geo-engineering" approaches considered so far appear to be afflicted with some combination of high costs, low leverage, and a high likelihood of serious side effects. Consequently, at

this juncture, no contribution to mitigation can be counted upon from this direction.

The second approach—increasing removal rates of GHG and soot from the atmosphere—has considerable promise, above all in the domain of afforestation and reforestation (wherein building up the global "standing crop" of trees pulls CO_2 out of the atmosphere and stores it in wood and soil organic matter). The total carbon currently stored in all the world's vegetation is estimated at 500-700 billion tonnes of C; increasing this by as much as 20% seems unlikely, and that would take care of only 100-150 billion tonnes of the 600-900 billion tonne requirement. (Whether the carbon stocks in soil, as opposed to vegetation, can be increased at all in a warming world is unclear; the higher temperatures may well increase decomposition rates on the average, driving carbon out of the soil and into the atmosphere.)

The preceding two points mean that a heavy share of the mitigation burden necessarily falls on reducing the offending emissions. In this connection there is important progress to be made in reducing emissions of the non-CO_2 heat-trapping substances, most importantly methane and black soot but also nitrous oxide, halocarbons, and the precursors of tropospheric ozone. The progress that can be made with all of these, however, may well not be more than is needed just to counterbalance reductions that are expected in the emissions of light-reflecting particles and their sulfur-oxide and nitrogen-oxide precursors. (Such reductions, which by reducing cooling influences will have a warming effect, are motivated by the desire to reduce the large public-health and acid-rain impacts of these particles.)

The "bottom line" is that a large part of the required mitigation effort must come in the form of reducing emissions of carbon dioxide. A modest (but still valuable) piece of this can come from reducing deforestation rates in the tropics, which today are adding perhaps 1-2 billion tonnes of C per year to the atmosphere. But the biggest target has to be the over 7 billion tonnes per year of carbon coming from fossil-fuel combustion.

The leverage for reducing the CO_2 emissions from fossil fuels can be understood by representing those emissions as a four-fold product:

C emissions = *population* x *GDP/person* x *energy/GDP* x *C/energy*.

Let us consider each of the contributing factors in turn:

Population. Lower is better for many reasons. If world population were 8 billion in 2100 rather than the mid-range UN forecast of about 10 billion, holding down the carbon emissions from the energy to make everybody prosperous would be that much easier. Fortunately, reduced population growth can be achieved by measures that are attractive in their own right (notably improving health care, reproductive rights, and educational opportunities for women).

GDP per person. This is not a lever that most people would want to use to reduce emissions, because higher GDP/person is generally considered preferable to lower. People are not getting rich as fast as they think, however, if GDP growth is

being achieved at the expense of the environmental underpinnings of well-being. Internalizing environmental costs of economic growth (including those of climate change) may slow that growth a bit, but probably not by very much. In addition, changes in lifestyle in industrial and other urban regions can be envisioned that would increase quality of life even though they reduced GDP (e.g., shorter commutes to work, or replacing physical commuting with telecommuting).

Energy intensity of GDP. Getting more GDP out of less energy—that is, increasing energy efficiency—has been a long-term trend. (On a global basis, the improvement has been averaging about 1% per year for decades.) The process of achieving this entails deploying more efficient cars, trucks, planes, buildings, appliances, and manufacturing processes, as well as structural shifts in the economy (toward less energy-intensive forms of economic activity) and increasing the efficiency with which primary energy forms are converted to electricity and portable fuels. These trends could be substantially accelerated. Indeed, this domain undoubtedly offers the largest, fastest, cheapest early leverage on carbon emissions.

Carbon intensity of energy supply. The ratio of C emitted in CO_2 per unit of primary energy supplied to the economy has also been falling, but more slowly than the energy intensity of GDP. The principal leverage for reducing this ratio more rapidly is in accelerating the introduction of low-carbon and no-carbon energy-supply options, notably nuclear energy, renewables, and advanced fossil-fuel technologies that can capture the CO_2 for sequestration away from the atmosphere.

How much may be demanded of measures to reduce these last two ratios—the energy intensity of economic activity and the carbon-emissions intensity of energy supply—can be illustrated by a somewhat oversimplified but still instructive calculation of the combinations of such reductions that would be needed to get on the above-described 550-ppmv stabilization trajectory under the assumption that population growth and growth of GDP per person proceed on a course that maintains real economic growth worldwide at 2.4% per year over the course of the 21st century.[10] In round numbers, what the calculation shows is as follows:

If the recent historical rate of reduction of energy of intensity of GDP worldwide, 1% per year, were to persist over the entire century, the amount of non-carbon-emitting energy supply (renewables, nuclear, and advanced fossil-fuel technologies with carbon capture and sequestration) needed to be on the 550-ppmv stabilization trajectory would be 800 exajoules per year in 2050 and 1500 exajoules per year in 2100. (This is to be compared with 100 exajoules from these sources in 2004 and 400 exajoules from fossil-fuels in that year.)

If the historical rate of reduction of energy intensity could be increased by half, from 1% to 1.5% per year over the whole world and the whole century, the need for non-carbon-emitting energy supply for the 550-ppmv stabilization trajectory would still grow to nearly 400 exajoules by 2050 and 800 exajoules by 2100.

Only if the historical rate of reduction of energy intensity could be doubled to 2% per year over the whole world and the whole century could the need for non-

carbon-emitting energy supply by 2100 be held to "merely" the 400 exajoules per year being provided by fossil fuels in 2004.

The requirements for non-carbon-emitting energy supply would be significantly larger still, of course, for the 450-ppmv stabilization trajectory.

What emerges from these figures is the clear finding that success in addressing the climate-change challenge is likely to require enormous efforts *both* on increasing the pace of energy-intensity reductions worldwide *and* on accelerating the deployment of non-carbon-emitting energy sources in place of the conventional fossil-fuel technologies that dominate today's global energy system. Nothing remotely like the needed scale of effort on *either* front is happening today. (After all, the "business as usual" projection—a prescription for climate-change catastrophe—was constructed by assuming continuation of more or less what is currently going on.)

Interaction of the Oil-Dependence and Climate-Change Problems

If the oil-dependence problem is a 600-pound gorilla already in the room, the climate-change problem is an 800-pound gorilla in the process of beating down the door. Society does not have the luxury of concentrating its efforts on the first problem with the expectation of turning to the second one later. The two must be addressed together, with attention to the ways in which they interact.

The good news in this respect is that there are a number of "win-win" approaches that can reduce both oil-dependence and climate-change risks at modest cost—or even, as Amory Lovins has long been energetically pointing out and an increasing number of corporations have been demonstrating, at a profit.[11] Sharply increasing passenger-vehicle fuel economy offers large potential in this category, as do advanced biofuels and a wide range of technical improvements in energy-intensive industrial processes.

The bad news, on the other hand, is that some approaches to reducing oil dependence would make the climate-change problem worse. Conspicuous in this category is the production of synthetic petroleum substitutes from tar sands, oil shales, and coal-to-liquid technologies, all of which entail large increases in CO_2 emissions per liter of delivered liquid fuel unless approaches are chosen that capture and sequester much of the CO_2 that otherwise is emitted during production of such liquids.

The "peak oil" debate—about when world production of conventional oil will peak and begin to decline, as well as about the consequences to be expected when this occurs—is thought by some to be germane to the climate issue in the sense that passing the oil-production peak might mark the beginning of a transition away from civilization's dependence on fossil fuels overall and thereby an amelioration of the CO_2 emission driver of global climate change. But there is little agreement among specialists about whether peak oil is 5 years away or 50, and even less agreement about whether its occurrence will precipitate a shift away from fossil fuels or just a shift among them—with production of liquids from

solid fossil fuels as described above (or from unconventional natural gas resources) taking over the burden from conventional petroleum.

I suggest that for purposes of energy-policy planning today it does not really matter very much who is right about peak oil. The economic and security perils of the world's current and growing dependence on oil tell us that we need to move smartly to reduce that dependence no matter whether peak oil is close or far away. And the looming danger of unmanageable climate change tells us that we must choose ways to do this that reduce rather than increase the energy sector's emissions of CO_2.

THE ROLE OF INNOVATION

The multiplicity of challenges at the intersection of energy with the economy, the environment, and international security—led by the oil-dependence and climate-change challenges just described—add up to a need for policies designed for two ends:

- to help society find and implement a satisfactory compromise among competing economic, environmental and security objectives—which includes trying to leave the biggest margins of safety against the biggest dangers—given the resources and technologies available at any given time, and
- to accelerate the processes of energy-technology innovation that, over time, can reduce the limitations of existing energy options, can bring new options to fruition, and thereby can reduce the tensions among energy-policy objectives and enable faster progress on the most critical ones.

These ends cannot be achieved by markets alone, without supplementary policies, because many of the goals relate to public goods (such as national security and meeting the basic energy needs of society's poorest members) and externalities (such as air pollution and greenhouse gases) that are not priced in markets unless policies achieve this.

A further implication of the characteristics of today's energy challenges is that society will do better to pursue a broad portfolio of improved energy-supply and end-use options, rather than putting its eggs in too few baskets. The merits of such diversity are manifold: it provides flexibility to respond to changing conditions and new information (an "insurance policy" for an uncertain world), including providing the possibility of discarding options that ultimately prove unsuitable; it takes into account that, even after all plausible technological improvements, there comes a point in the expansion of any energy option where rising marginal costs and/or risks make further expansion unattractive (meaning a broad portfolio is likely to have lower costs and risks overall than a narrower set of options wherein each has to bear too much of the load); and by combining the growth of multiple new or improved options—each drawing on different types of material resources, skills, and firms—it can replace status quo technologies more rapidly than would be possible by one or two new options alone.

The need for deployment of technologies of energy supply and end-use better

than those that now dominate the energy system is acute. Without an accelerated transition to improved technologies, societies will find it increasingly difficult—and in the end probably impossible—*either* to limit oil imports and oil dependence overall without incurring excessive economic and environmental costs *or* to provide the affordable energy needed for sustainable prosperity everywhere without intolerably disrupting the Earth's climate. They will not be able to improve urban air quality while meeting growing demands for personal transportation; not be able to use their abundant coal resources without intolerable impacts on regional air quality and acid rain; not be able to expand the use of nuclear energy enough to make a difference for climate change and oil and gas dependence while still reducing the risks of accidents, nuclear terrorism, and nuclear-weapon proliferation.

Major innovations in both technology and policy are urgently needed but not currently materializing at the pace that is required.

In this context, the needed process of innovation in energy technology must be understood as not consisting only of research and development (R&D), but also of at least equal emphasis and resources devoted to *demonstration* at commercial scale and in diverse contexts of the technological improvements that R&D have made possible and to mechanisms to promote *accelerated deployment* of those demonstrated options that offer the greatest leverage for reducing important externalities and enhancing important public goods.[12] The energy-technology-innovation "pipeline" is full of potentially valuable—even potentially crucial—technologies at every stage of development, and it is no less important to push along toward full commercialization those that are already close to that threshold than to be doing the applied research and early development needed to move forward the more "far out" possibilities. Indeed, the need for rapid response to the linked oil-dependence and climate-change challenges means that the world cannot afford to wait for such long-term possibilities as fuel-cell-powered vehicles and fusion to come to fruition. This is not to say that that investment in such long-term options is not essential, for it is; but it should not replace or come at the expense of the needed efforts to move nearer-term, oil-sparing, climate-friendly options into the marketplace.

INADEQUACY OF ENERGY INNOVATION EFFORTS

Current efforts in energy-technology research, development, and demonstration (RD&D)—and in accelerated deployment of the best options that such RD&D produces—are woefully inadequate in relation to the scale of the challenge and the size of the opportunities.[13] U.S. public and private spending on energy-technology RD&D totals only $5-6 billion per year, less than one percent of what this country spends for electricity and fuels. The situation in other industrialized countries

(with the conspicuous exception of Japan) is no better, and in developing countries it is worse.

Around the world, the energy sector's ratio of RD&D investments to total revenues is well below that for any other high-tech sector of the economy. In a $45 trillion world economy (calculated using purchasing power parities), fueled by circa $3 trillion worth of energy, total public and private investments in energy RD&D appear to be in the range of $15-20 billion, hence something like half a percent of energy expenditures and 0.03 percent of world GDP. These investments will need to be boosted at least 2-3-fold if the world is to meet the energy challenges it faces in the decades immediately ahead.

In principle, such an increase should not be difficult to achieve, given the modest sums involved in relation to the scale of the energy enterprise. In the United States, for example, a tripling of the federal government's expenditures on energy technology RD&D could be financed with a increase of about 2 cents per gallon in the federal tax on gasoline. In practice, however, governments have proven extremely reluctant to increase energy RD&D expenditures, even when their rhetoric would appear to call for such increases. Again the case of the United States provides an instructive example: despite the Bush Administration's consistent rhetoric (including very conspicuously in President Bush's January 2006 State of the Union address) to the effect that advances in energy technology will hold the key to addressing the oil-dependence and climate-change challenges, the appropriations for energy RD&D have been essentially level in real terms since Fiscal Year 2001, and the President's FY2007 budget request is for less money for this purpose than the Congress appropriated for FY2006.[14]

Private-sector expenditures for energy RD&D are more difficult to track in detail because of lack of comprehensive and consistent data, but such analyses as are available for the case of the United States suggest that these investments have been falling overall.[15] The reasons usually adduced for such a decline include generally low oil and gas prices (until recently) and a corporate financial environment that has placed particular emphasis on short-term rates of return (to which R&D investments contribute little). Government tax incentives for corporations to undertake more R&D are mostly modest, and the incentive of recent higher oil and gas prices for RD&D on alternatives is weakened by industry uncertainty about whether these recent prices will persist. Perhaps most importantly in the context of the character of energy challenges as elaborated in this article, companies are likely to continue to under-invest in developing and deploying low- and no-carbon energy options until there is a stronger marketplace incentive for such action, either in the form of a substantial carbon tax or its practical equivalent in the form of economy-wide emissions caps implemented through tradable permits.

CONCLUSIONS: WHAT SHOULD BE DONE?

Accelerated improvement of the energy-supply and energy-end-use technologies available and propagating in the marketplace will be essential if the suite of ener-

gy challenges confronting the world in this century—most compellingly the coupled problems of oil dependence and climate change—are to be successfully addressed. Bringing about the needed pace of energy-technology innovation will require major innovations in policy and management, aimed at

- providing the scale, continuity, and coordination of effort in energy research, development, and demonstration needed to bring an appropriate portfolio of improved options to the threshold of commercialization in a timely way;
- promoting and financing early deployment of the most promising options to emerge from the RD&D process, in order to accelerate their progress down the learning curve toward market competitiveness;
- ensuring that improved energy technologies not only diffuse rapidly through the industrialized countries and the relatively prosperous urban sectors of developing ones, but also reach the least developed countries and sectors;
- devising and implementing an adequate, equitable, and achievable global framework for limiting global emissions of greenhouse gases;
- more effectively mobilizing the power of partnerships—among countries, levels of government, and the public, private, academic, and NGO sectors—in achieving all of the preceding ends; and
- more effectively communicating to the broad public the reasons all this must be done and the benefits to be gained and dangers averted by doing it, in order to develop and sustain the needed political support.

Numerous major, high-level, multi-sectoral studies conducted in the United States over the past decade—and similar efforts internationally—have arrived at more or less the same recommendations and have elaborated what carrying them out would entail.[16] Insights about what to do and how to do it, then, are not lacking. What has been and remains missing is political leadership at the level needed to make it happen. Let us hope this changes soon.

We invite reader comments. Email <editors@innovationsjournal.net>.

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6. Some of the increase in damages from storms and floods is due to the growth of population and infrastructure in the vulnerable regions, but increasingly persuasive data and analysis relating to rising trends in extreme precipitation events and the most powerful tropical cyclones (hurricanes and typhoons) indicate that global climate change is also a factor.
7. These figures correspond to a scenario that the IPCC called IS92a, a mid-range trajectory among many studied by the IPCC in an extensive modeling exercise using a range of assumptions about the future size and composition of economic activity and about technological change. A similar result for the dominant CO_2-emission driver of climate change can be obtained much more simply by assuming that real economic growth worldwide averages 2.4% per year over the 21st century, the energy intensity of economic activity declines at 1.0% per year, and the carbon intensity of energy supply (carbon emitted in CO_2 per unit of primary energy supplied to the economy) declines at 0.2% per year. These rates of decline of energy intensity and carbon intensity correspond to recent global experience and so are often characterized as "business as usual" values; the economic-growth figure is a mid-range value among projections found in the literature.
8. James Hansen, A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? *Climatic Change*, vol. 68, pp 269-279, February 2005, <http://www.columbia.edu/~jeh1/hansen_slippery.pdf>.
9. This criterion needs to be stated in terms of probabilities because of remaining uncertainties in the relation between the CO2 concentration and the size of the global-average surface temperature increase. This relation is called the "sensitivity" of the climate and is expressed as the size of the temperature increase corresponding to a doubling of the pre-industrial CO_2 concentration. Sensitivity is thought to be between 1.5 and 4.5°C, with a "best estimate" in the middle of this range at around 3°C.
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